Rotorcraft performance data for AEDT

Methods of using the NASA Design and Analysis of Rotorcraft tool for developing data for AEDT's Rotorcraft Performance Model

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13. ABSTRACT (Maximum 200 words)

This report documents use of the NASA Design and Analysis of Rotorcraft (NDARC) helicopter performance software tool in developing data for the FAA's Aviation Environmental Design Tool (AEDT). These data support the Rotorcraft Performance Model (RPM) developed for AEDT. The methods are primarily intended to support helicopters which do not have sufficient information in their flight manuals to develop data using the methods documented in DOT-VNTSC-FAA-16-03. The process of developing performance data for RPM using NDARC is detailed for a piston engine training helicopter.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yard	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
		NOTE: volumes greater than 1000 L shall be shown in m³		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.314	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgments

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List of Abbreviations

Abbreviation	Term
AEDT	Aviation Environmental Design Tool
AEE	FAA Office of Environment and Energy
AFE	Above Field Elevation
CAS	Calibrated airspeed
DOT	Department of Transportation
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
HIO	Helicopter, fuel injected, horizontally opposed
HNM	Heliport Noise Model
HP	Horsepower
ICAO	International Civil Aviation Organization
IGE	In Ground Effect
INM	Integrated Noise Model
IRP	Intermediate Rated Power
ISA	International Standard Atmosphere
KCAS	Knots calibrated airspeed
KTAS	Knots true airspeed
MAP	Manifold Air Pressure
MCP	Maximum Continuous Power
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
NASA	National Aeronautics and Space Administration
NDARC	NASA Design and Analysis of Rotorcraft
NM	Nautical Miles
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OGE	Out of Ground Effect
ROC/D	Rate of Climb/Descent
RPM	Revolutions per Minute – in the context of engine or rotor speeds
RPM	Rotorcraft Performance Model – in the context of modeling performance
SAE	Society of Automotive Engineers
TAS	True airspeed

Executive Summary

This report documents usage of the NASA Design and Analysis of Rotorcraft (NDARC) software tool to develop helicopter performance data for the Rotorcraft Performance Model (RPM) in the FAA's Aviation Environmental Design Tool (AEDT). This document is a follow-on the original RPM documentation.

The helicopters included in the original RPM document were those which had flight manual performance data sufficiently detailed to generate the required data. These data typically are fuel consumption and power required as a function of helicopter weight, altitude, and flight speed.

A significant fraction of the helicopter fleet are small piston engine helicopters which do not have detailed performance information in their flight manuals. Particular examples of helicopters lacking this type of data are the Robinson R22 and R44, which are among the most popular helicopters in the world by the number of registered airframes.

Because the R22 and R44 represent a significant fraction of the fleet, FAA and Volpe made the decision to pursue using NDARC to develop the performance data for these helicopters. The use of NDARC for this purpose was validated in the development of the original RPM process by comparing the NDARC results against the flight manual performance information for the Bell 407.

This report presents the extension of the NDARC performance methods developed for the Bell 407 to the R22 and the R44. Unlike the Bell 407, no verification and validation (V&V) of the R22 and R44 is possible, since these data don't exist in their flight manual. We do note, however, that the NDARC results make physical sense, in that the NDARC calculated operating empty weights are comparable to the manufacturer's reported weights and the power required for the heaviest weights and highest flight speed are comparable to the maximum continuous power available for the engines used on the particular helicopters.

Based on this comparability of the NDARC results with the helicopter's physical characteristics, and the prior V&V of the general RPM methods, we believe the results are usable and constitute a significant improvement over the mode-based helicopter fuel consumption methods currently in AEDT. *The authors recommend using the methods and data of RPM to replace the mode-based helicopter performance currently in the AEDT.*

1. Introduction

This report is a follow-on to the original Rotorcraft Performance Model (RPM) documentation (Senzig & Boeker, 2015). That report documented the RPM methods and provided data for a number of turboshaft-powered helicopters and a single reciprocating engine helicopter. The data for the particular helicopters in the original report came from their respective flight manuals.

For some helicopters, the flight manuals do not contain sufficient information to generate the data required for the RPM method. In particular, the Robinson R22 and R44 flight manuals do not have these data. These helicopters are important for environmental modeling since together they represent 12.6% of the global helicopter fleet, and 21.2% of the AEDT helicopter fleet, as measured by number of registered airframes in 2014. The data in Table 1 below show the helicopters in the current version (3.21) of the AEDT Fleet database and their registered number in the global fleet.

Table 1, Helicopters in AEDT Fleet

HELO_ID	HELO_DESCR (Helicopter description)	Number
A109	Agusta A-109	1192
B206L	Bell 206L Long Ranger	2327
B212	Bell 212 Huey (UH-1N) (CH-135)	3459
B222	Bell 222	87
B206B3	Bell 206B-3	3589
B407	Bell 407	1382
B427	Bell 427	82
B429	Bell 429	258
B430	Bell 430	118
BO105	Boelkow BO-105	663
CH47D	Boeing Vertol 234 (CH-47D)	1126
EC130	Eurocopter EC-130 w/Arriel 2B1	597
H500D	Hughes 500D	2117
MD600N	McDonnell Douglas MD-600N w/ RR 250-C47M	62
R22	Robinson R22B w/Lycoming 0320	3121
R44	Robinson R44 Raven / Lycoming O-540-F1B5	5297
S61	Sikorsky S-61 (CH-3A)	405
S65	Sikorsky S-65 (CH-53)	189
S70	Sikorsky S-70 Blackhawk (UH-60A)	4833
S76	Sikorsky S-76 Spirit	776
SA330J	Aerospatiale SA-330J Puma	462
SA341G	Aerospatiale SA-341G/342 Gazalle	841
SA350D	Aerospatiale SA-350D Astar (AS-350)	3767
SA355F	Aerospatiale SA-355F Twin Star (AS-355)	649
SC300C	Schweizer 300C / Lycoming HIO-360-D1A	1591
SA365N	Aerospatiale SA-365N Dauphin (AS-365N)	738

2. Background

The original impetus for developing the RPM for AEDT was a recognition by the FAA's Office of Environment and Energy (AEE) that the improvements in aircraft environmental performance modeling for fixed-wing aircraft, particularly the improvements in fuel consumption modeling, were not being paced by similar improvements in rotorcraft environmental modeling. The development of the RPM was a response to that need.

The original RPM report primarily used flight manual information as the source of rotorcraft performance data. For a number of important helicopter types, the flight manuals do not contain enough information to generate the data required for the RPM. Section 12 of the original report briefly mentions the possible use of the NASA Design and Analysis of Rotorcraft (NDARC) model (Johnson, 2016) as a potential source of helicopter performance data for those vehicles which don't have adequate flight manual data. There is a risk that using NDARC to develop the performance data may introduce bias, since the helicopters lacking flight manual information tend to be smaller vehicles, which may represent an extrapolation from the data used to develop the NDARC methods.

This report focuses on the data development of the Robinson R22. Similar methods were used for the R44. Note that Wayne Johnson, the developer of the NDARC program, provided the NDARC data for the Lycoming O-540 engine used on the R44. The authors of this report developed the NDARC data for the Lycoming O-320 engine used on the R22.

3. NDARC Data

Each section in this chapter represents a major component field in the NDARC input data files. Samples of NDARC input files are included in the Appendices. We use `courier font` in this report to indicate NDARC file names, RPM support tools, or the names of variables within files used by NDARC or the support tools. Note that the NDARC engine performance data discussed in section 3.1 are found in a file associated with the helicopter's engine (a `*.list` file); the helicopter definition data found in sections 3.2 through 3.5 are found in the file associated with the helicopter (a `*.airc` file); the performance run information is in a job file (a `*.njob` file); and the outputs of the process are in a `*.out` file.

3.1 Engine performance data

This section discusses translating the data from the engine performance charts developed by Lycoming into the NDARC format.

The Robinson Helicopter Company has manufactured the R22 with a number of different engines. The engine discussed in this report is a Lycoming O-320-B engine (Textron Lycoming, 1973), which is installed on the particular helicopter (an R22 Beta - pictured on the cover of this report) used to develop the AEDT noise data for the R22 (Reherman, 2005).

The Lycoming O-320-B engine has a normal rating of 160 horsepower (HP); in the R22, the engine is limited to a maximum continuous power rating (MCP) of 124 HP, and a 5 minute takeoff rating of 131 HP. The 5 minute takeoff rating corresponds to the intermediate rated power (IRP) discussed in the original RPM document. The Lycoming performance chart for this engine is presented below in Figure 1.

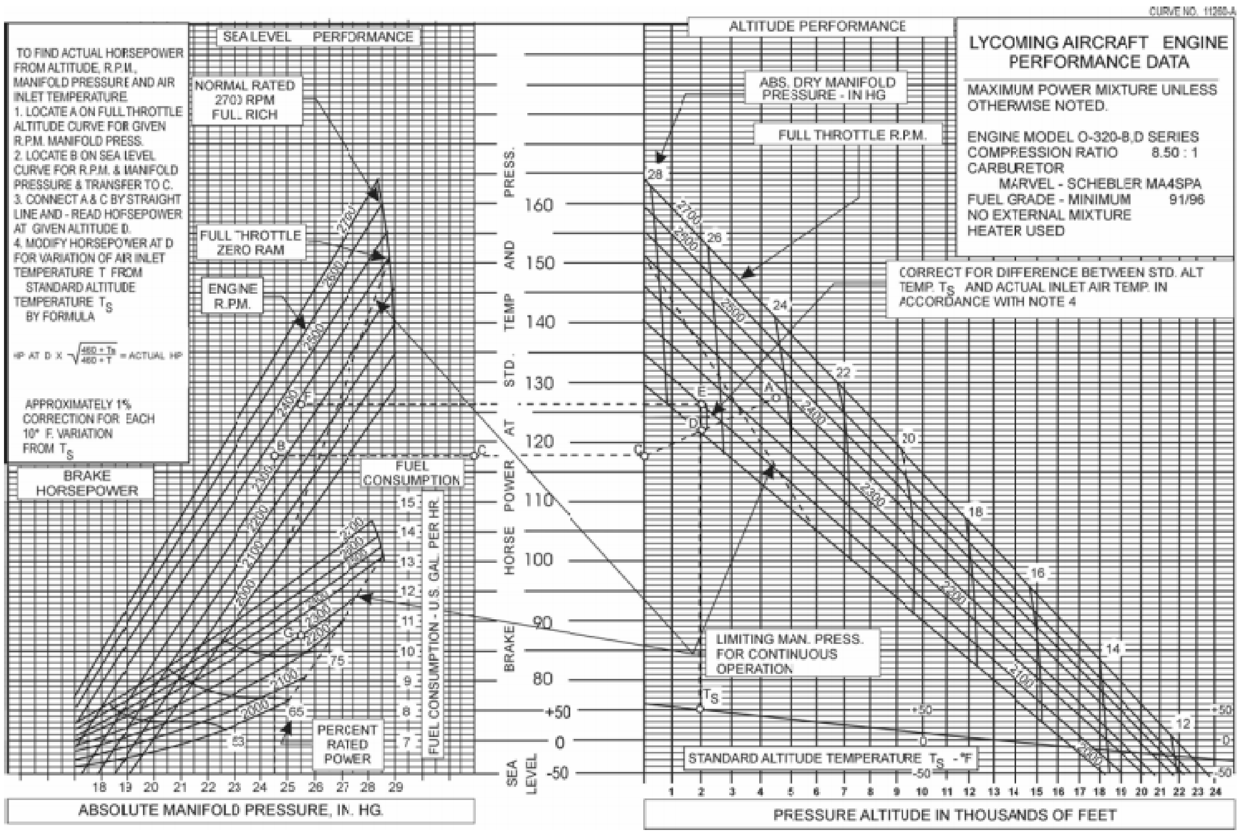

Figure 1, Lycoming O-320 performance chart

The chart provides both the power available from the engine and the fuel consumption required to generate that power. The table below lists the fuel consumption at the normal 2652 RPM operating speed of the R22; the first two columns of data in this table come from Figure 1, the other columns are calculated.

Table 2, Lycoming O-320 fuel consumption

Horsepower	gal/hour	Power (% MCP)	lb/hour	Kg/sec
125	11	100.8%	66.0	0.008316
115	10.4	92.7%	62.4	0.007862
105	9.6	84.7%	57.6	0.007257
100	9.2	80.6%	55.2	0.006955
90	8.5	72.6%	51.0	0.006426
80	7.7	64.5%	46.2	0.005821

The data from Table 2 are either interpolated or extrapolated to the standard fuel consumption format used in RPM; these fuel consumption data are given in Table 3 below.

Table 3, R22 fuel consumption in Rotorcraft Performance Model format

Power (% MCP)	Kg/sec
7%	0.001508
10%	0.001733
20%	0.002483
30%	0.003233
40%	0.003983
50%	0.004732
60%	0.005482
70%	0.006232
80%	0.006913
85%	0.007282
90%	0.007657
100%	0.008271

3.1.1 Engine weight

NDARC provides a weight estimate equation which includes terms describing constant, linear, and exponential relationships with horsepower. Since we know the weight of the engine and its rating, we can determine the weight coefficients. The engine weight equation in the NDARC manual (section 22-8) is:

$$W_{engine} = K_{0eng} + K_{1eng}P + K_{2eng}P^{X_{eng}}$$

Where W_{eng} = Weight of the engine in pounds

K_{xeng} = weight coefficients

P = Horsepower of engine at specified rating (MCP in this case)

X_{eng} = power scaling exponent

For the O-320B, the rated power at MCP is 124 HP and the engine weighs 285 pounds, so the K_{1eng} term is set to 1.78125 (lb/HP). The other weight coefficient terms are all set to zero, so the weight estimate equation becomes linear with respect to horsepower.

3.1.2 Engine reference parameters

NDARC uses a number of reference parameters to determine the engine performance. The following sub-sections discuss these parameters and where they can be found in the Lycoming and Robinson documentation.

3.1.2.1 Reference power

The reference power (P0_ref in the NDARC input file) is the rated power of the engine. The Lycoming manual lists the reference power for this engine at 160 HP.

3.1.2.2 Reference specific fuel consumption (SFC)

The reference specific fuel consumption (sfc0_ref in the NDARC input file) is the specific fuel consumption in units of pounds (mass) of fuel per hour per horsepower. The data for the reference SFC come from the Lycoming chart presented in Figure 2 below. The SFC is about 0.52 at the reference power of 160 HP.

3.1.2.3 Reference fuel-Air ratio

The reference fuel-air ratio (F0_ref in the NDARC input file) is a generic fuel-air mass ratio for reciprocating engines, and is set equal to 0.08.

3.1.2.4 Reference critical power

The reference critical power (Pcrit_ref in the NDARC input file) is the thermodynamic limit on how much power the engine can produce. The value of 164 HP is the maximum power shown in Figure 1; this occurs at the maximum RPM of 2700 and is set by the manifold pressure limits of the air intake system.

3.1.2.5 Reference engine speed

The reference engine speeds (N0_ref and Nspec_ref in the NDARC input file) are set by the MCP given by Robinson in the R22 flight manual. The MCP of 124 HP is given at an engine speed of 2652 RPM. Note that this corresponds to a setting of 104% on the helicopter's tachometer.

3.1.3 Engine scaling parameters

For the R22, we don't need the engine scaling parameters since we have data for the exact engine used on the helicopter. The engine scaling parameters used in the NDARC file are those given in the documentation for generic scaling based on the original data from the method's theoretical source (Taylor, 1966).

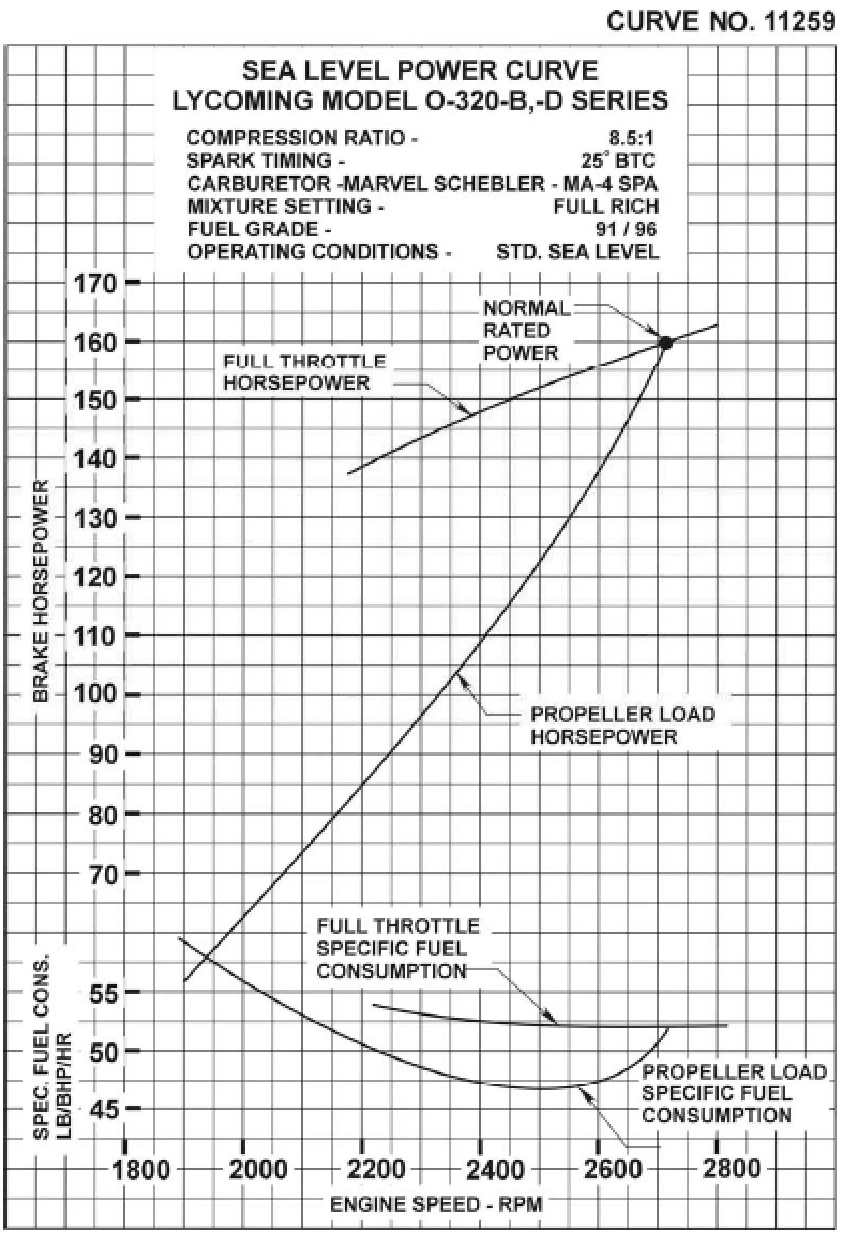

Figure 2, Lycoming O-320 specific fuel consumption

3.1.4 Engine power available

The method of determining the engine power available is given in section 22-5 of the NDARC documentation. The NDARC equation which defines the power available is:

$$P_a = P_0 K_P (\sigma + \Delta\sigma_M) r^{X_{pN}} \theta^{X_{p\theta}}$$

Where P_a = power available (HP)

P_0 = reference power (HP)

K_P = scaling constant (dimensionless)

σ = density ratio (dimensionless)

$\Delta\sigma_M$ = $\left(\frac{\gamma-1}{2}\right)M^2$ (dimensionless)

γ = ratio of specific heat (1.4, dimensionless)

M = Mach number (dimensionless)

r = engine speed ratio (N/N0, dimensionless)

X_{pN} = speed ratio exponent (dimensionless)

θ = temperature ratio (dimensionless)

$X_{p\theta}$ = temperature ratio exponent (dimensionless)

The value of K_P is determined by using the reference power of 124 HP (the MCP) and an available power of 160 HP (the rated power of the engine). We calculate a sea level static condition (where the temperature and density ratios are unity) of K_P = 160/124 = 1.29 at the reference RPM.

The speed ratio and temperature ratio exponents are calculated by extracting the data from the right side (the ‘altitude performance’) of the engine performance chart (Figure 1). In this case, we extracted the data for engine speeds of 2100, 2300, 2500 and 2700 RPM at altitudes from sea level to 18,000 feet in increments of 2000 feet. This gave us 40 records of data. We ran a statistical fit through these data using the NDARC engine power available equation. We assumed no ram effect of forward motion on the engine, so the Mach term was zero. The results of this statistically development gave a best fit of X_{pN} of 0.722 and $X_{p\theta}$ of 0.719. Compared to the Lycoming data, the equation with these constants gives results which differ by a maximum of about 5% at the highest altitudes and the lowest RPM – conditions under which the R22 can’t actually fly. For the flight regions actually expected – low altitudes and high engine speeds - the differences are less than 2%.

3.1.5 Performance at the power required

The data required in NDARC when the helicopter’s engine power is less than the MCP is the specific fuel consumption as a function of the fractional power used. The SFC data are presented as a linear function of the reference SFC discussed in section 3.1.2.2. For our usage, the data can be converted from the format given in Table 3 above to that given in Table 4 below. Note that ‘`Pffq`’ and ‘`Kffq`’ in Table 4 are terms used in NDARC to represent the power ratio and the SFC ratio. NDARC also allows the user to define the fuel consumption through an empirical polynomial equation, but the method of using SFC as a function of the power required closely resembles the method used in RPM, so this relatively simple translation was used for the R22. Table 8 in Appendix B contains data for the polynomial fuel flow coefficients for the R44.

Table 4, R22 fuel consumption in NDARC format

Power fraction (Pffq)	SFC fraction (Kffq)
0.07	0.186
0.10	0.213
0.20	0.306
0.30	0.398
0.40	0.490
0.50	0.583
0.60	0.675
0.70	0.767
0.80	0.851
0.85	0.896
0.90	0.942
1.00	1.018

3.2 Main and tail rotor data

The current version of RPM is intended to work with conventional helicopters with a single main rotor and an anti-torque tail rotor. This is a data structure limitation rather than a fundamental limitation of the underlying methods. This section discusses the data requirement for the current RPM data structures.

3.2.1 Main rotor

NDARC allows the user to define the rotor system using data at different levels of detail depending on the data and information available to the user. For the R22 and R44, only fairly limited sets of data are available, but those data sets are sufficient for the lowest level of rotor system definition required by NDARC.

3.2.1.1 Main rotor system sizing data

The numerical data required for NDARC which defines the rotor system are given below. The `courier font` variable name after the semi-colon indicates the name of the variable in the NDARC file.

Rotor speed data:

V_{tip} = blade tip speed relative to the hub (feet per second); `Vtip_ref`

Rotor shaft limit data:

P_{limit} = limiting power at rotor shaft (HP); `Plimit_rs`

f_{limit} = scaling constant for limiting power (dimensionless); `fPlimit_rs`

Parameter data:

Radius = blade hub to tip distance (feet); `radius`

σ = ratio of blade area to swept area (dimensionless); `sigma`

N = number of blades (dimensionless); `nblade`

T_L = linear blade twist angle (degrees); `twistL`

Taper = tip to root chord ratio (dimensionless); `taper`

The other data in the rotor definition section are either generic data, or flags which set the methods of NDARC processing. These generic data and the processing method flags are discussed in the NDARC documentation.

3.2.2 Tail rotor

NDARC uses the same data structure for the tail rotor as for the main rotor system. Note that not all data listed above are required; NDARC provides default values in some cases.

3.3 Control surface data

NDARC allows the user to define the horizontal and vertical tails of the helicopter. This improves the accuracy of the helicopter weight and drag estimates. The geometric data typically come from 3-view drawings of the helicopter; the maximum speed data come from the flight manual.

Geometry:

V_{tail} = Tail volume (dimensionless); `TailVol`

AR = Aspect ratio (dimensionless); `AspectRatio`

Taper = ratio of the surface's tip chord to the root chord (dimensionless); `taper`

Sweep = Quarter chord sweep angle (degrees); `sweep`

Thickness = thickness to chord ratio (dimensionless); `thick`

Weight:

VNE = maximum aircraft speed, never exceed (knots); `Vdive`

Note that the tail volume used here is not the tail volume used for fixed wing aircraft. In this case, the tail volume is a ratio of "volumes", where the volume is really an area multiplied by an arm (distance). So the volume does have units of length cubed, but the physical meaning is more akin to a torque (a force at a distance), where the area of the surface is proportional to the force it can exert. For helicopters, the numerator of the volume ratio is the surface area times the distance from the hub to the quarter-chord of that surface. The denominator is the swept area of the main rotor times the main rotor radius.

3.4 Fuselage dimensional data

The fuselage data required by NDARC, like the control surface data, are used to size the helicopter for weight and drag estimations. The data can be extracted from 3-view drawings of the aircraft.

$Nose_L$ = Length of the nose (feet); `Length_nose`
$Fuse_W$ = Width of the fuselage (feet); `Width_fus`
$Fuse_H$ = Height of the fuselage (feet); `Height_fus`
$Boom_C$ = Circumference of the tail boom (feet); `Circum_boom`
$Boom_W$ = Width of the boom (feet); `Width_boom`

3.5 Fuel

This section of the NDARC process defines the capacity of the fuel system on the vehicle and also provides some ability to trim the fuel system weights.

Wt_{fuel} = Weight of fuel in the main fuel tank when full (pounds); `Wfuel_cap`
Wt_{aux} = Weight of fuel in the auxiliary fuel tank when full (pounds); `Waux_cap`

3.6 Performance cases

We define performance runs for the NDARC process with the goal of generating the data required for the RPM process. The inputs which define the NDARC performance runs are therefore constructed with the understanding that the output of those runs will be used as the input to define the RPM process. We are essentially using NDARC to replace the performance charts normally found in a helicopter's flight manual.

As discussed in the original RPM document, the data required are the speed, weight, power required and fuel consumption at a particular altitude and temperature for the helicopter of interest. We have control over the inputs (speed, weight, altitude, and temperature) and NDARC, for these inputs, provides the required outputs (power required and fuel consumption).

Each run in NDARC is a termed a 'performance condition'. At each condition, we set the weight of the helicopter and its true airspeed. The default environmental conditions are sea level standard; this standard defines the altitude and the temperature. We also set the control forces such that the helicopter is assumed to be in trim for the given flight condition.

For bookkeeping purposes, we run each job at a constant weight with the airspeed varying from a minimum speed above hover (30 knots for the R22) to a speed near the maximum (110 knots for the

R22). We increment these speeds by 20 knots in each run to provide a relatively smooth speed profile. We use a different design weight for each run; we use three weights, again to provide a reasonable distribution, with the range from the lightest weight expected (OEW plus a pilot and minimum fuel), up to the maximum takeoff weight (MTOW) of the helicopter. Note that Table 7 in Appendix A has only a single airspeed; the other airspeeds were removed for brevity.

3.7 NDARC outputs

NDARC provides a plethora of outputs. Most of these are not needed for the RPM process, but the wealth of intermediate outputs allows the user to assess the reasonability of the process to determine where, if anywhere, errors may have crept into the process.

The final NDARC data that are required by RPM are the fuel consumption and the power required for the given flight condition. These data are given in the Flight Conditions output section, under the Propulsion Group data. Power required is reported in standard units of horsepower, and the fuel consumption (fuel flow) is given in units of pounds per hour. Details of the rotor system components power requirements are given in the Flight State section of the output, but these are details outside of the scope of the current version of the RPM – we note the existence of these component-level power requirements should RPM ever be upgraded – e.g. to use the component power requirements to assist in the prediction of component-level noise.

4. RPM support tools

RPM support tools are required to convert the NDARC outputs into the RPM input data. At this point in the process, we have helicopter performance data in the raw format of weight, speed, power, and fuel consumption at particular environmental conditions from NDARC. This section discusses converting these NDARC data into a format usable by the RPM program.

4.1 CTCP program

We can convert the raw data into the normalized, parametric data of RPM with a program written by Volpe staff. The program, `HELI_CTCP.exe`, performs the rote task of converting the outputs of NDARC (or data read from a performance chart) into the format expected by the RPM process. The two sub-sections below discuss the inputs and the outputs of the program.

4.1.1 CTCP inputs

The primary input file to the `HELI_CTCP` program is the `flow_airspeed` file; this is a csv file which contains header information describing the format of the file, followed by tabular data for each of the helicopter weights from the NDARC run (or from the performance chart). An example from the R22 follows in Figure 3. Note that the text box is cut off so that only two of the three weight groups are shown – the file does contain the third group.

4.1.1.1 CTCP header

The first line of the file contains the name of the rotorcraft under consideration ('`R22`'). The next line ('`WEIGHTS`') is just a header line for the weights index. The next line ('`3`') is the weight index which indicates that there are three weight groups used in this file. The next line ('`SPEED`') is a just a header line for the speed index. The next line ('`6`') is the speed index – there are six speeds in each weight group. Note that the speed index sets the size of the array; the table can be populated with artificial data, but rows can't be left blank.

4.1.1.2 CTCP curves

The first line after the end of the main header is a header line ('`CTCQ curve one`') indicating the start of the first weight group. The next line ('`ALTITUDE`') is a header line after which the following data line contains the altitude information ('`0`' or zero feet MSL). Note that temperature information is not explicitly given; the `HELI_CTCP` program assumes ISA conditions at the given altitude. The next two lines are the weight header ('`WEIGHT`') and the weight ('`1100`' - in pounds) for the data group. These data are followed by another header line ('`KTAS, LB_PER_HOUR, PERCENT_TORQUE`') for the data group. The data that follow this should have the same number of rows as the speed index discussed in sub-section 4.1.1.1.

The rows of data in this group are the true airspeed in knots, the fuel flow in pounds per hour, and the percent of power (synonymous with torque, since RPM is constant) relative to MCP. In Figure 3, a second weight group (for 1200 pounds, also at 0 MSL) is also given. Note that in the actual file, the data in the record fields are comma separated.

R22		
WEIGHTS		
3		
SPEEDS		
6		
CTCQ curve one		
ALTITUDE		
0		
WEIGHT		
1100		
KTAS	LB_PER_HOUR	PERCENT_TORQUE
10	46.2	58
30	34.7	41
50	33.6	39
70	38.8	47
90	50.1	64
110	67.8	94
CTCQ curve two		
ALTITUDE		
0		
WEIGHT		
1200		
KTAS	LB_PER_HOUR	PERCENT_TORQUE
10	50	64
30	36.9	44
50	35	41
70	39.8	48
90	51	66
110	68.41	95

Figure 3, CTCP inputs for R22

4.1.2 CTCP outputs

The output of the CTCP program is shown in Figure 4 below. Unlike the input file, this is a space-delimited file. The format of the file follows the standard set by the original U.S. Army helicopter performance program on which RPM is based (Kiwan, 1994). The speed values have been normalized to the non-dimensional µ (mu), the weight values to the non-dimensional coefficient of thrust (CT), and the thrust values to CQ (the non-dimensional coefficient of torque, which is the same as the non-dimensional coefficient of power - CP). The data are repeated in the second data group because the original program assumed that more than one main rotor data set would be available. Because we only

```
Card1: N_MU N_CT
 7  3
Card2: MU
0.000 0.025 0.075 0.126 0.176 0.226 0.276
Card3: CT
 20.61  22.49  24.36
Card4: CQD1(I,J) Rows are I, Columns are J
 21.57  22.63  23.74
 14.23  15.71  17.18
 10.06  10.80  11.78
  9.57  10.06  10.55
 11.53  11.78  12.27
 15.71  16.20  16.44
 23.07  23.31  23.56
Card5: CQD2(I,J) Rows are I, Columns are J
 21.57  22.63  23.74
 14.23  15.71  17.18
 10.06  10.80  11.78
  9.57  10.06  10.55
 11.53  11.78  12.27
 15.71  16.20  16.44
 23.07  23.31  23.56
Card7: CQ1_VTIP CQ2_VTIP
671.0 673.0
```

Figure 4, CTCP outputs for R22

have one rotor RPM data set, we repeat the data at two slightly different rotor tip speeds, with the RPM program interpolating (between identical data sets) back to the single tip speed.

Note that the output file contains seven µ values, but that the input only had six. The CTCP program adds the hover speed (µ = 0), based on the calculations of the power required for the out-of-ground effect hover (HOGE) discussed in the original RPM document. The number of weight (CT) entries is the same in both files.

4.2 RPM program

At this point, assuming that the RPM data files required to define the helicopter have been populated, the RPM program can be run. A sample of a departure (the AEDT standard departure for this helicopter) is given in Table 5 below. The track (the latitude and longitude) are part of the inputs; the distance (nautical miles), altitude and airspeed are also defined by the profile. The outputs of the process are the time, power (HP), and fuel flow (Flow – in units of kg/sec). In the third row, the helicopter is vertically ascending to 15 feet AGL in 3 seconds; the required power to do this at the MTOW of 1370 pounds is 157 HP, which is within the capability of the engine (which is rated to 160 HP), but is outside the capability of the helicopter (which is limited to an IRP of 131 HP).

Table 5, R22 Standard AEDT departure

Lat	Lon	Time	Distance	Altitude	Airspeed	HP	Flow	Weight
42.46994	-71.289	0	0	0	0	11.2	0.0015	1370
42.46994	-71.289	30	0	0	0	80	0.0047	1369.9
42.46994	-71.289	60	0	0	0	156.8	0.0081	1369.6
42.46994	-71.289	63	0	15	0	124	0.0067	1369.5
42.46976	-71.2893	68.64	0.02	15	30	115.5	0.0064	1369.4
42.46885	-71.2907	75.78	0.1	30	53	124	0.0067	1369.3
42.46251	-71.3004	114.91	0.67	1000	53	124	0.0067	1368.8
42.46163	-71.3018	118.89	0.75	1000	91.8	110	0.0061	1368.7
42.45062	-71.3187	158.11	1.75	1000	91.8	110	0.0061	1368.2
42.4396	-71.3357	197.32	2.75	1000	91.8	110	0.0061	1367.6
42.42858	-71.3526	236.54	3.75	1000	91.8	110	0.0061	1367.1
42.41755	-71.3696	275.75	4.75	1000	91.8	110	0.0061	1366.6
42.40652	-71.3865	314.97	5.75	1000	91.8	110	0.0061	1366.1
42.3955	-71.4034	354.19	6.75	1000	91.8	110	0.0061	1365.5
42.38446	-71.4203	393.4	7.75	1000	91.8	110	0.0061	1365
42.37343	-71.4372	432.62	8.75	1000	91.8	110	0.0061	1364.5
42.36239	-71.4541	471.83	9.75	1000	91.8	110	0.0061	1363.9
42.35136	-71.471	511.05	10.75	1000	91.8	109.9	0.0061	1363.4
42.34032	-71.4879	550.26	11.75	1000	91.8	109.9	0.0061	1362.9
42.32927	-71.5048	589.48	12.75	1000	91.8	109.9	0.0061	1362.3
42.31822	-71.5217	628.7	13.75	1000	91.8	109.9	0.0061	1361.8
42.30718	-71.5386	667.91	14.75	1000	91.8	109.9	0.0061	1361.3
42.29612	-71.5554	707.13	15.75	1000	91.8	109.9	0.0061	1360.7
42.29256	-71.5609	719.77	16.08	1000	91.8	109.9	0.0061	1360.6

5. Recommendations

The authors believe the RPM process and the associated data development methods are sufficiently mature to begin the discussion of transitioning the process and the data into a future version of AEDT. This section discusses some of the aspects of this transition.

5.1 Data transition

We need to transition the helicopter performance data from the current RPM text and CSV files to the SQL data structures of AEDT. For most of the data files this will involve a one-for-one translation from a text file to a corresponding SQL table. The one data set where issues may develop is the CTCP tabular data discussed in section 4.1.2. For this data set, the structure of the data is not consistent between helicopter types: the number of weight curves can vary, as can the number of speeds. The current version of the RPM handles this inconsistency by using a separate CTCP file for each helicopter; AEDT's SQL would not use a system of discrete tables for each aircraft.

We expect the level of effort to translate the RPM data to SQL to be on the order of one month for a developer. The majority of this time would be designing the database.

5.2 Process transition

The RPM code is currently in Fortran 90. The code needs to be translated into C# for AEDT. Before this can be done, a code review should be done by a developer. After the code review, and any major issues uncovered have been addressed, the translation to C# can be done. One known deficiency in RPM is the lack of taxi operation modeling.

After the translation and the database importation, the results of processing a set of test trajectories and helicopters should be compared against the results with the Fortran 90 RPM implementation, and, where the data are available, against manufacturer flight manual data. After this verification and validation effort, the methods should be documented for inclusion in both the AEDT User Manual and the AEDT Technical Manual.

We expect the level of effort of the process translation to be on the order of six months of developer time. The comparison of methods and final documentation are expected to be on the order of one month of developer time.

6. References

Johnson, W. (2016). *NASA Design and Analysis of Rotorcraft, Theory, release 1.10.* Moffett Field: NASA Ames.

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Reherman, C. R. (2005). *Fitchburg Municipal Airport Noise Measurement Study: Summary of Measurements, Data, and Analysis.* DOT-VNTSC-FAA-03-09.

Senzig, D. A., & Boeker, E. R. (2015). *Rotorcraft Performance Model (RPM) for use in AEDT.* Cambridge, MA: U.S. Department of Transportation. Retrieved from http://ntl.bts.gov/lib/56000/56200/56284/Rotorcraft_Performance_Model.pdf

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Textron Lycoming. (1973). *Operator's Manual, O-320 series aircraft engines.* Williamsport, PA: Part No. 60297-16.

Appendix A: Robinson R22 NDARC data

Table 6, R22 Engine data (O320B)

```
&DEFN action='ident',created='September 2016',
      title = 'Lycoming O-320-B Engine',
 &END
 &DEFN quant='RecipModel',&END
 &VALUE
 ! Reciprocating Engine Model
      title = 'Lycoming O-320-B Engine',
      ident = 'O320B',
 ! Engine Ratings
      nrate = 1,
      rating = 'MCP',
 ! Weight (285 lb), Theory 1.10, section 22-8
      Kwt0_eng =       0.000,
      Kwt1_eng =       1.78125, ! Lycoming Manual O-320, page 2-5, B-series
      Kwt2_eng =       0.000,
      Xwt_eng  =      0.0000,
 ! Reference
      P0_ref     =      160.,  ! Lycoming Manual O-320, page 2-2, B-series
      sfc0_ref   =      0.52,  ! Lycoming Manual O-320, page 3-17 graphic
      F0_ref     =      0.08,  ! Generic ratio
      SF0_ref    =        0.,  ! no jet thrust
      Pmep_ref   =      0.,    ! no MEP limit
      Pcrit_ref  =      164.,  ! Lycoming graphic 3-6, page 3-18
      N0_ref     =     2652.,  ! Robinson R-22, page 1-5, Beta-series
      Nspec_ref  =     2652.,
 ! Scaling, section 22-7, generic - don't change
      Xo =  0.2,
      Xs =  0.3,
      Xf =  0.1,
 ! Power Available, section 22-5
      Kp         =      1.29, ! Forces reference power of 160 HP
      Kram       =        1.,
      XpN        =       0.722,
      Xpt        =       0.719,
      Xcrit      =        0.,
 ! Performance at Power Required, section 22-6
    ! fuel flow (piecewise linear)
      MODEL_Kffq=2,
      Xffq  =      0.0, ! independent of engine speed
      Nffq  =       12,
      Pffq(1,1) =0.07, 0.1,  0.2, 0.3,  0.4, 0.5,  0.6, 0.7,  0.8, 0.85, 0.9, 1.0,
      Kffq(1,1) =0.186,0.213,0.306,0.398,0.490,0.583,0.675,0.767,0.851,0.896,0.942,1.018,
   ! jet thrust installation
      Kfgr  =   1.00,
 &END
```

Table 7, R22 run performance file

```
&JOB OPEN_status=1,&END
 &DEFN action='ident',created='Sep 16 2016',title='standard input',&END
 !################################################################################
 &DEFN action='read file',file='O320B.list',&END
 &DEFN action='read file',file='R22_min.airc',&END
 !================================================================================
 &DEFN quant='Cases',&END
 &VALUE
    title='R22',
    TASK_size=0,TASK_mission=0,TASK_perf=1,
    OUT_design=0,OUT_perf=0,OUT_geometry=0,
    OUT_aircraft=0,OUT_solution=0,OUT_sketch=0,
    WRITE_input=0, ! Setting the WRITE parameters to zero shuts down the verbose output
    WRITE_input_TechFactors=0,
    WRITE_input_Geometry=0,
    WRITE_wt_level=1, ! see Dictionary, page 34
    WRITE_wt_comp=0,
    WRITE_flight=0,
    WRITE_sketch_load=0,
 &END
 !&DEFN quant='Size',&END
 !&VALUE title='design',nFltCond=0,nMission=0,&END
 !&DEFN quant='Solution',&END
 !&VALUE !trace_maxgw=1,trace_fly=1,
     !trace_miss=1,
 !&END
 !================================================================================
 &DEFN quant='Performance',&END
 &VALUE
    title='performance analysis',nFltCond=1,
 &END
 &DEFN quant='PerfCondition',&END
 &VALUE
    title='fix speed',label='V_10',
    SET_GW='input',Npass=0,
    GW=1300.,
    SET_max=0,max_quant='Pmarg',max_var='speed', ! FltState, Dictionary, page 54
    Vkts=10.,
  !  pitch=-5.,coll=5.,pedal=-5.,
    STATE_trim='free', ! Page 63
 &END
!================================================================================
 &DEFN action='endofcase',&END
 &DEFN action='endofjob',&END
```

Appendix B: Robinson R44 NDARC data

Table 8, R44 engine data (O540F)

```
&DEFN action='ident',created='January 2016',
      title = 'Lycoming O-540-F Engine',
 &END
 &DEFN quant='RecipModel',&END
 &VALUE
 ! Reciprocating Engine Model
      title = 'Lycoming O-540-F Engine',
      ident = 'O540F',
 ! Engine Ratings
      nrate = 1,
      rating = 'MCP',
 ! Weight (400 lb), Theory 1.10, section 22-8
      Kwt0_eng =       0.000,
      Kwt1_eng =       1.702, ! Lycoming Manual O-540, page 2-6, F-series
      Kwt2_eng =       0.000,
      Xwt_eng  =      0.0000,
 ! Reference
      P0_ref     =      235., ! Lycoming Manual O-540, page 2-2, F-series
      sfc0_ref   =      0.56, ! Lycoming Manual O-540, page 3-22 graphic
      F0_ref     =      0.08, ! Generic ratio
      SF0_ref    =        0., ! no jet thrust
      Pmep_ref   =      0.,   ! no MEP limit
      Pcrit_ref  =      265., ! Lycoming graphic 3-11, page 3-23
      N0_ref     =     2800., ! Lycoming Manual O-540, page 2-2, F-series
      Nspec_ref  =     2800.,
 ! Scaling, section 22-7
      Xo =  0.2,
      Xs =  0.3,
      Xf =  0.1,
 ! Power Available, section 22-5
      Kp         =      1.13, ! Maximum power available from Lycoming, 265 HP
      Kram       =        1.,
      XpN        =       0.6,
      Xpt        =       1.2,
      Xcrit      =        0.,
 ! Performance at Power Required, section 22-6
    ! fuel flow (polynomial)
      MODEL_Kffq=1,
      Kffq0 =     5.27,
      Kffq1 =   -18.52,
      Kffq2 =    23.22,
      Kffq3 =    -8.96,
      Xffq  =      0.2,
   ! jet thrust installation
      Kfgr  =   1.00,
 &END
```

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